Etude No. 143
IGM84-086-143

Selected Topics for Fatigue and Fracture Research

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CNRC 23370

Table of Contents

		Page
1.	Introduction	1
2.	Steel and Aluminum Alloys	2
3.	Wood Structures	7
4.	Oil and Grease Products	10
5.	Transportation Units	11
6.	Components	12
	References	15
	Appendix 1	17

Introduction

Discussions have been carried on with 21 selected companies and research centers across Canada representing a range of industrial interests including metal production, energy, transportation, timber and oil products. The discussions covered two subjects:

1. The nature of fatigue- and fracture-related problems that were carried out by the individual industry or its customer, and
2. The possible role of IMRI in developing a cooperative research program with any of the surveyed industries for the purpose of improving the quality and the competitive marketability of its Canadian products.

The companies and research centers and the representatives who took part in this study are listed in Appendix 1.

The following sections summarize the activities of these industries in the field of fatigue and fracture and discuss the possible role of IMRI in promoting such activities.

1 - Steel and Aluminum Alloys

The four major steel producers in Canada are Steelco, Dofasco, Sydney Steel and Algoma Steel with a total capacity of approximately 14 million gross tons. Principal products could broadly be described as plates, hot and cold rolled sheets, pipes, cast steel for railway rails and rolling stock as well as finished and semi-finished products.

In the area of fatigue and fracture, research efforts are carried out by the industry through joint research programs with several research centers across Canada. In-house research trends over the years have focused on the property characterization of commonly used alloys involving metallurgical and mechanical analysis of basic microstructure and monotonic properties. Limited studies related to the fatigue life performance under different loading and environmental conditions were also carried out by the manufacturers and the users, specially in areas of finished and semi finished products.

Over the years joint research projects have also been developed between industries and canadian research centers; an excellent example of this is the work being carried out by the Welding Institute of Canada and CANMET. In the case of CANMET, extensive fracture studies were made on high strength pipe line steels to determine the dynamic fracture toughness characteristics and aspects of crack initiation and propagation under the influence of different corrosive environments, see Ref (1-6).

However, due to the fact that the steel industry has been slow in adopting new technology and upgrading their in-house capabilities, high quality, low priced off-shore steel is gaining a share of the Canadian steel market.

This emphasizes the need to improve the quality of canadian steel and to open new areas of application. Increased research in fatigue and fracture mechanics could be a positive element toward this objective. In this direction the American Iron and Steel Institute has recently published a report entitled "Research on Sheet Steel as an Automative Structural Material" in an attempt to establish research priorities for industry in automative applications. Suggested research studies in the area of fatigue have been outlined in this report and could be adopted by Canadian steel manufacturers.

In the aluminum industry the trend is very similar; the bulk of canadian production is manufactured by Alcan Limited and Reynolds Inc.,both of which are subsidiaries of foreign establishments. Their ingot and casting capacity covers a range of extruded products, such as plates, sheets and semi-finished products intended for customers in transportation, energy, components and structural industries.

Research efforts made by these producers are, again, a form of classical property characterization of commonly used alloys, with a limited contribution towards alloy development. Interest has also been focused on the effect of welding techniques on residual stresses and the life expectations of welded joints. An example of this is the failure analysis being carried out on 5080-0 and 5080-3 Al alloys in the design of LNh freestanding tanks and on 2024-T3 and 2014-T6 clad aluminum skin materials for the design of the DeHavilland S.T.O.L. aircraft, see Refs. (7,8)

In these two major industries, however, a distinction must be made between aspects of characterization in commonly used steel and aluminum alloys and

the fundamental fracture research areas for which IMRI is suited. As a result of discussions with four manufacturers in these areas, four potential areas of research have been established; these are :

1 - Effect of manufacturing aspects on fracture properties of steel and aluminum alloys; this includes differences in alloy-making processes such as ingot and casting methods, ratio of alloying elements, methods of cooling as well as cooling rate and coatings.

2 - Effect of operational and environmental parameters; this includes

i - Welding techniques (spot vs. fusion)

ii - prestrain and overloading effects on ductility exhaustion

iii - various corrosive elements and their relation to mechanisms of crack initiation and propagation.

iv - temperature effect (in its isothermal and cyclic mode) on strain rate and deviation from linear summation of damage

3 - Test and quality performance techniques where research could focus on the establishment of test standards for thin sheets and determine optimum thickness effect on limits of plane strain - plane stress fracture transition. It also includes design and construction of high resolution test equipment to detect surface cracks for the purpose of quantifying internal damage.

B - Suggested Research Topics

1 - Establishment of fatigue resistant characteristics in flash-butt welded regions of rail steel. The effect of variation of fracture toughness properties of rail web, should be included in this, see Figure 1.

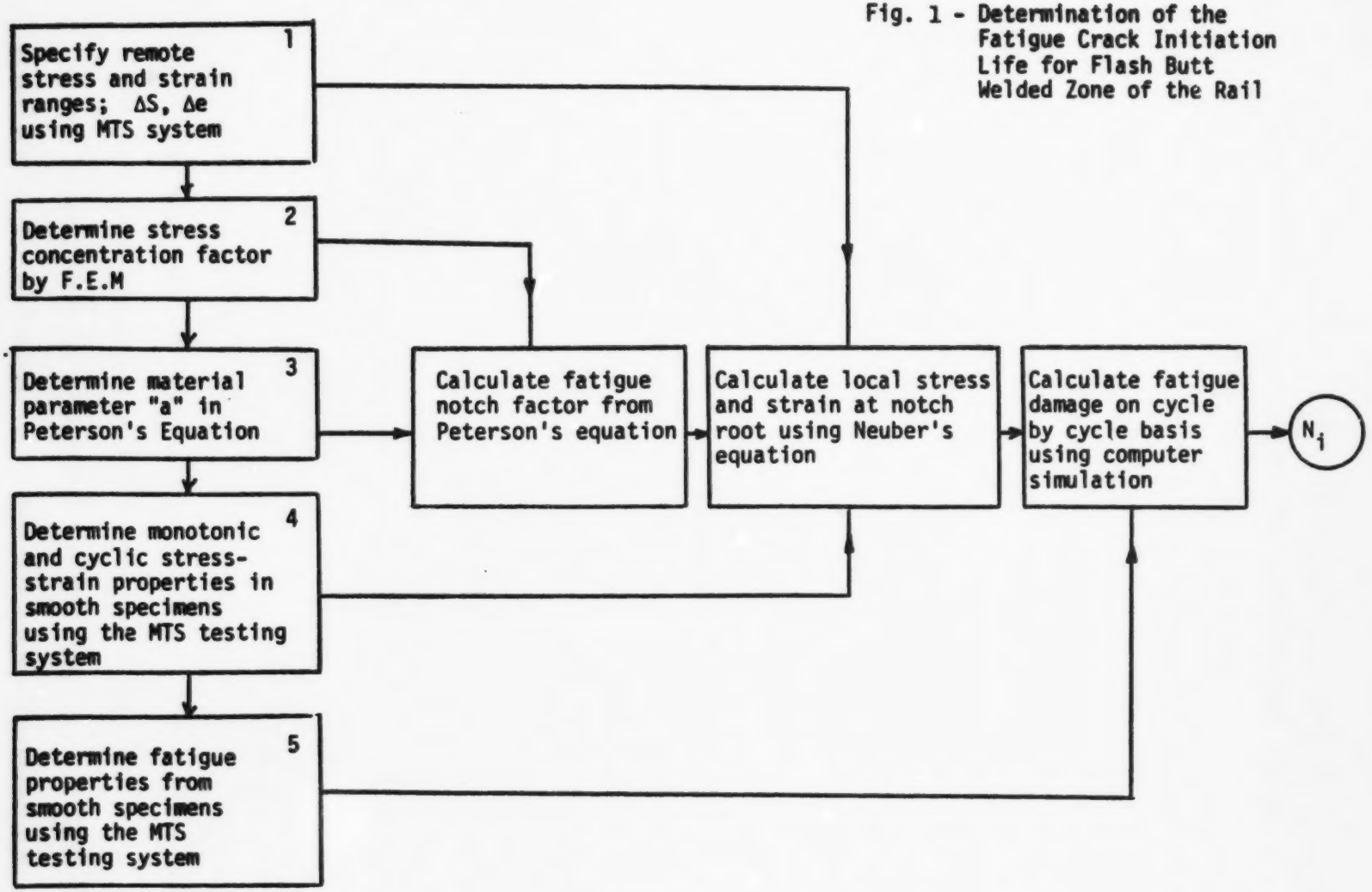
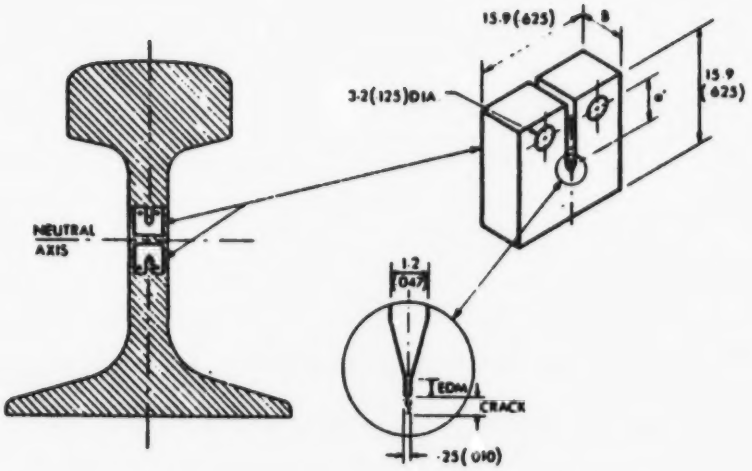

1
Specify remote stress and strain ranges; ΔS, Δe using MTS system
2
Determine stress concentration factor by F.E.M
3
Determine material parameter "a" in Peterson's Equation
4
Determine monotonic and cyclic stress-strain properties in smooth specimens using the MTS testing system
5
Determine fatigue properties from smooth specimens using the MTS testing system
Calculate fatigue notch factor from Peterson's equation
Calculate local stress and strain at notch root using Neuber's equation
Calculate fatigue damage on cycle by cycle basis using computer simulation
N_i

Fig. 1 - Determination of the Fatigue Crack Initiation Life for Flash Butt Welded Zone of the Rail



mm inch

W = 13.5 (0.531)

B = 6.6 (0.26)

$\bar{a}$ = 7.5 (0.297)

a = $\bar{a}$ + EDM + CRACK

Fig. 3 Dimensions of Compact Specimens from the Center of the Rail Web

Effect of welding-induced properties on the mechanisms of crack initiation and propagation and total damage accumulation in aluminum complex structure should also be studied (Alcan)

2 - Effect of energy losses in structural aluminum and steel on the crack jump distance and the instantenous value of the stress intensity factor, see Ref. (9-11). In this analysis would concentrate on:

i - energy dissipation at the crack tip during rapid crack propagation.

ii - characteristics of the initial arrest phase where reorientation could occur.

This investigation of energy loss is of special interest with regard to the prediction of the size of the run or arrested crack extension during rapid internal cooling of a cylindrical pressure vessel.

An area of interest to Steelco Inc. is also the determination of a relationship between the stress intensity factor and the crack tip velocity in the high velocity region. This study is important in explaining the factors affecting the design of reliable crack arrestors for large structures such as in ship hulls or large vessels and containers. A candidate material would be the domestic X-65 steel.

An essential test component in this project is the multiple spark, high speed recording system.

2 - Wood Structures

In general wood could be viewed as an anisotropic, inhomogeneous material which contains numerous checks, voids and other flaws. Because of this inherent nature, it would appear that the load carring behavior of wooden structures should be analyzed using fracture mechanics rather than using

a simple continuum strength theory. Only within the last 10-15 years have fracture mechanics studies been done on wood, see Figure 3.

In Canada preliminary investigations into fracture mechanics interpretation of wood failure began in the 1960's with the work of Atack, et al (12). More comprehensive work was done on flakeboard fracture and elevated temperature fracture, see Refs. (13-17). Barret and Foschi (18) presented important work on Mode II fracture of western hemlock. Fracture mechanics analysis of laminated wood beams has also been studied by Smith and Penney (19) while White and Green (20) considered the fracture of wood-adhesive bonds. The effect of crack-front width on fracture toughness of Douglas-Fir was also studied by Barret (21) as was shear strength of uniformly loaded dimensional lumber and creep rupture for different wood species.

More work, however, is needed in this field to determine the critical stress intensity factors of sharp cracks and notches in commercially important wood species covering the range or temperature and moisture content encountered in structural application. This field provides IMRI, in cooperation with Fointek Canada Corporation, an opportunity to demonstrate the range of applicability of the LEFM concept in the establishment of a design code for wood structures. In this direction three suggested research areas are:

1. Evaluation of stress intensity factors for wood species in mixed mode fracture.
2. Development of a fracture property data bank for soft- and hard-wood species subjected to different environmental parameters, such as moisture and subzero temperatures.

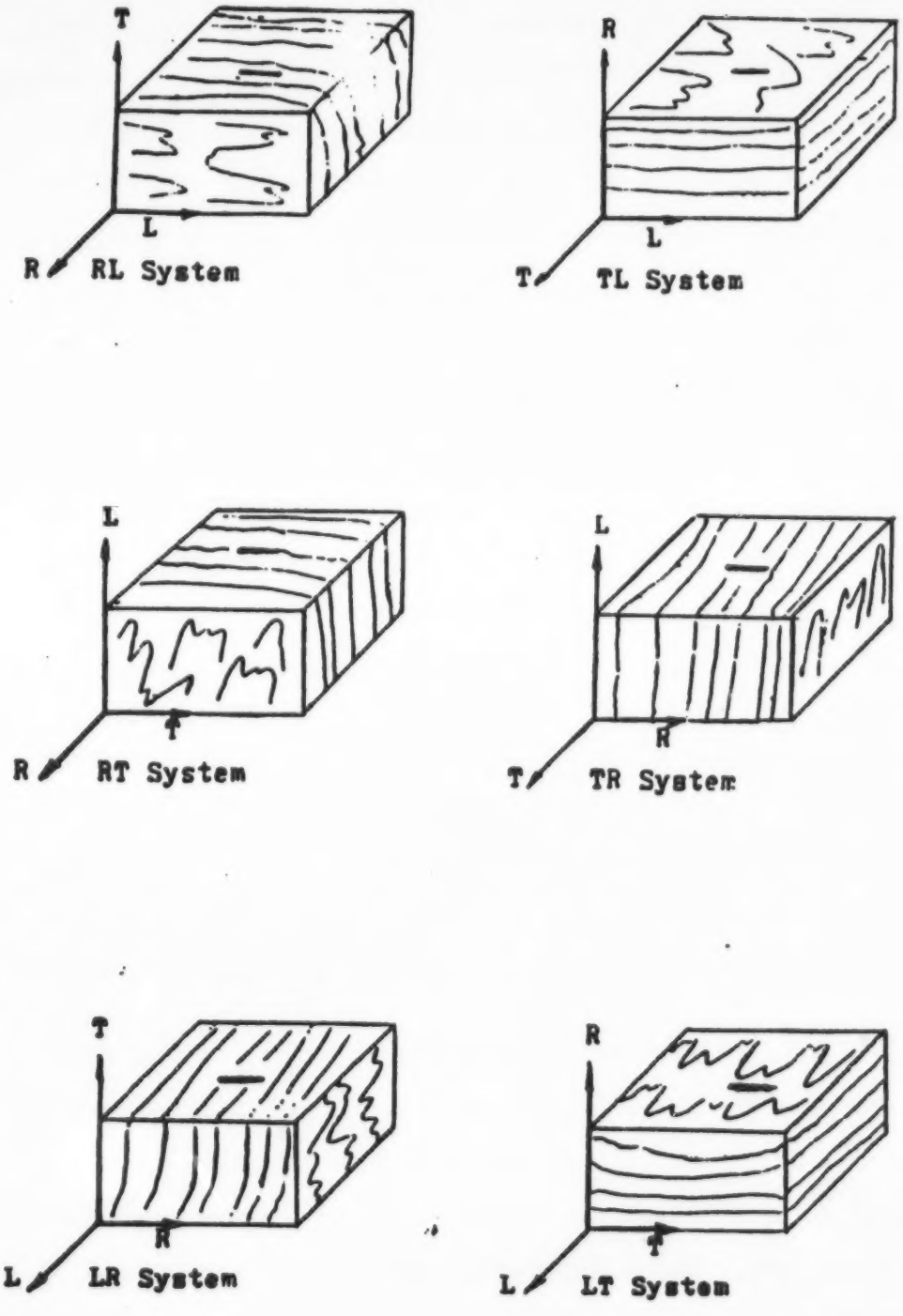


Figure 1. The Six Principle Crack Propagation Systems in Wood for each Particular Mode of Deformation.

3. Study of fracture characteristics in epoxy impregnated wood structures where a significant increase in the load carrying capacity of such injected structures has been observed.

3 - Oil and Grease Products

In rolling contact applications such as gears, bearings, wire rope and similars a grease product acting as a lubricant influences the magnitude of maximum pressure and the coefficient of friction between the two rolling surfaces. While this is a beneficial mechanism that may result in reduction of surface wear and subsurface contact stresses it promotes the appearance of surface microcracks leading to surface failure. Lubricants penetrating surface cracks could also accelerate the growth rate by inducing elastohydrodyanmics pressure on the crack tip during crack closure. Another element in accelerating crack growth is the effect of the water content in the lubricant that could act as a corrosive agent at the crack tip.

In 1979 Imperial Oil carried out a series of tests using a four-ball tester to develop a fatigue inhibited lubricant for tranportation applications. In this test three lubricants were tested; the base grease, the fatigue inhibited base grease both with and without water contamination. Results of this work demonstrated that water did not decrease fatigue life and that the fatigue inhibitor did decrease fatigue life. This test was repeated to verify such observations. Since these observations were not consistent with general expectations a more comprehensive research effort to optimize the base for fatigue properties was suggested. While such work is extremely important for many industries that utilize lubrication in rolling contact applications no further efforts were carried out to extend this investigation. In this

subject the Institute could, in cooperation with the Imperial Oil or Shell Canada and the Western Laboratories of NRCC in Vancouver, perform basic analyses on various grease products using instrumented Timken, Falex or Four Ball testers. In this work the effect of lubricant additives and properties on crack initiation life under various Canadian environmental parameters should be established. Furthermore, the study of dynamic fracture aspects of branching and stress wave crack tip interaction that could be carried out using the suggested high velocity recording system, see page 7, could lead to valuable information in the field of oil and gas stimulation. Recovering can be enhanced by control of cracks initiated at the bore hole and propagated into the field.

4 - Transportation Units

The work of Burns and Tiplin (21) describes the Canadian fatigue research in the areas of marine transportation where extensive failure analysis was made during the design of Conch Ocean memberance and the Conch Liquified Natural Gas free-standing tanks. It also describes the fatigue efforts in the design, development and certification of the Dash 7 aircraft.

In the area of ground transportation companies such as Bombardier Inc. Dofasco and UTDC Research and Development Limited are involved in the design and building of advanced locomotives, trucks, vehicles and suspension systems. Fracture problems related to the strength of linkage bolts, welding failure of aluminum joints and plates, hair cracks in ride frames and bolsters were encountered. These problems were solved in most cases by replacing the failed component with a material of higher strength. Similar to the aircraft industry,

however, a critical element in the development of a ground transport unit is the gatigue performance of the complete unit as a complex structure subjected to various load spectrums. This requires the capability of full size test facilities,a wide range of load capacity and a large system of data acquisition. This form of testing is fundamentally different from the orientation of IMRI objectives. Therefore, it is the opinion of the author that IMRI's role with this industry could be limited to material selection and advice on fracture case studies.

5 - Components

Two component's producers took part in this study; Velan Engineering and Aviation Electronics. The first is a producer of power plant valves such as gate, check and globe valves for use in thermal and nuclear power plants in Canada, the U.S.A. and Europe. The size of these valves range from 1/4" to 30" diameter and they are manufactured by using carbon and stainless steel alloys such as SME 105 and SA-182 and 216. Design of these valves requires the knowledge of fatigue properties of the material, taking into account the power plant operating conditions such as variations in operating temperature and pressure as a function of time. This form of calculation is performed through the use of an ASME nuclear code

Aviation Electronics is a subsidiary of Bendix Corporation and has primary interest in the design and manufacture of gas turbine fuel control systems for Pratt and Whitney PT6 engines. The main alloys used in the fabrication of this system are stainless steel and aluminum. The role of fatigue and fracture research here is limited to material selection and choice of failure criterion for design of shafts, bearing components and other components in

the system. In these two examples, while no immediate or urgent research program in fatigue is required by either industry, a long term involvement in research areas that may effect the quality and reliability of the design and building of components subjected to thermo-mechanical loads spectrum is needed. Suggested research topics are:

1 - Design of a thermo-mechanical fatigue system to experimentally study the damage mechanisms in two high temperature alloys, AISI 316 stainless steel and L-605. The design of the testing system was the focus of extensive discussions between IMRI and Pratt & Whitney. High temperature fatigue research will not be advanced in IMRI without this system.

2 - Fatigue crack initiation in two phase $\alpha+\beta$ Ti alloys utilized in gas turbines for compressor blades and discs where several variations from 'traditional' fatigue behavior typifies the fatigue response of Ti alloys. For instance, at low cyclic stress ranges cracks are initiated internally in several different microstructural configurations such as equia ed $\alpha+\beta$ and $\alpha+\alpha$ or Widmanstatten $\alpha+\beta$ and for several $\alpha+\beta$ alloy composition. Cleavage of α phase, the β phase or environmental strain ageing were all proposed as mechanisms for internal crack initiation (23-25). At increased cyclic stress ranges, surface crack initiation prevails. However, the area of fracture surface in and around the origin is covered by facets, characteristic of brittle failure rather than striations associated with ductile material growth. Internal origins also exhibit facets in the area of initiation.

To accommodate both internal origins and facets at surface initiation sites without radically changing initiation mechanisms extremely localized plastic deformation is required. This permits the strain ageing process to block surface origins at low cyclic stress ranges and large number of cycles to failure. At increased stress ranges, crack growth is limited to a single crystallographic plane due to the low number of slip systems in the HCP structure and the strain ageing effects upon them.

It is proposed that IMRI in cooperation with Pratt & Whitney and Westinghouse Canada carry out a research program that investigates environmental effects on fatigue in Ti-6Al-4V. The originality in this research is that, if as suggested, environmental strain ageing controls the process, variations in atmosphere should enhance or retard internal origins depending upon the gaseous species producing strain ageing. Therefore the partial pressures of oxygen, nitrogen and hydrogen will be varied and the incidence of internal origins in each case determined.

The surface area at initiation sites covered by facets will also change. Less strain ageing will allow a greater number of active slip systems with a corresponding increase in striations and less facets. The opposite will apply for increased strain ageing. Therefore surface origin initiation site appearance will change with environment. This will be checked by detailed SEM observation of fracture surfaces. Plastic replication techniques should be capable of determining the density of surface slip lines for each environment. This data will be compared to the density produced by a normal environment and any differences could be explained by strain ageing phenomena.

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